The Futures of Particle Physics

Chris Quigg

Fermilab

Tevatron University

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From the 1898–99 University of Chicago catalogue:

“While it is never safe to affirm that the future of the Physical Sciences has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice . . . . An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals.”

Our Picture of Matter

Pointlike ($r \lesssim 10^{-18}$ m) quarks

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

and leptons

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

with interactions specified by

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

gauge symmetries . . .

A Decade of Discovery Ahead

- Higgs search and study; elucidate electroweak symmetry breaking / 1-TeV scale.
- CP violation in the B system
- Rare decays (K, D, ...)
- ν oscillations
- Top as a tool
- New phases of matter
- Exploration!
  Extra dimensions / new dynamics / SUSY / new forces and constituents
- Proton decay
- What kinds of matter and energy make up the universe?
- Particle astrophysics and astronomy; precision cosmology; astroparticles

The decade of discovery won't happen automatically . . .

- ▷ Many of our goals are difficult.
- ▷ Timely success is in doubt for many experiments.
- ▷ Getting to the answers is important!

. . . and neither will the glorious future that lies beyond.

- ▷ We've done too little to prepare alternative futures.
- ▷ The scope of our science has grown; funding has not.
- ▷ We are communicating the wonders of our science inadequately.

Elementarity

▷ Are quarks and leptons structureless?

Symmetry

▷ Electroweak symmetry breaking and the 1-TeV scale

▷ Origin of gauge symmetries

Unity

▷ Coupling constant unification

▷ Unification of quarks and leptons (new forces!); of constituents and force particles

▷ Incorporation of gravity

Identity

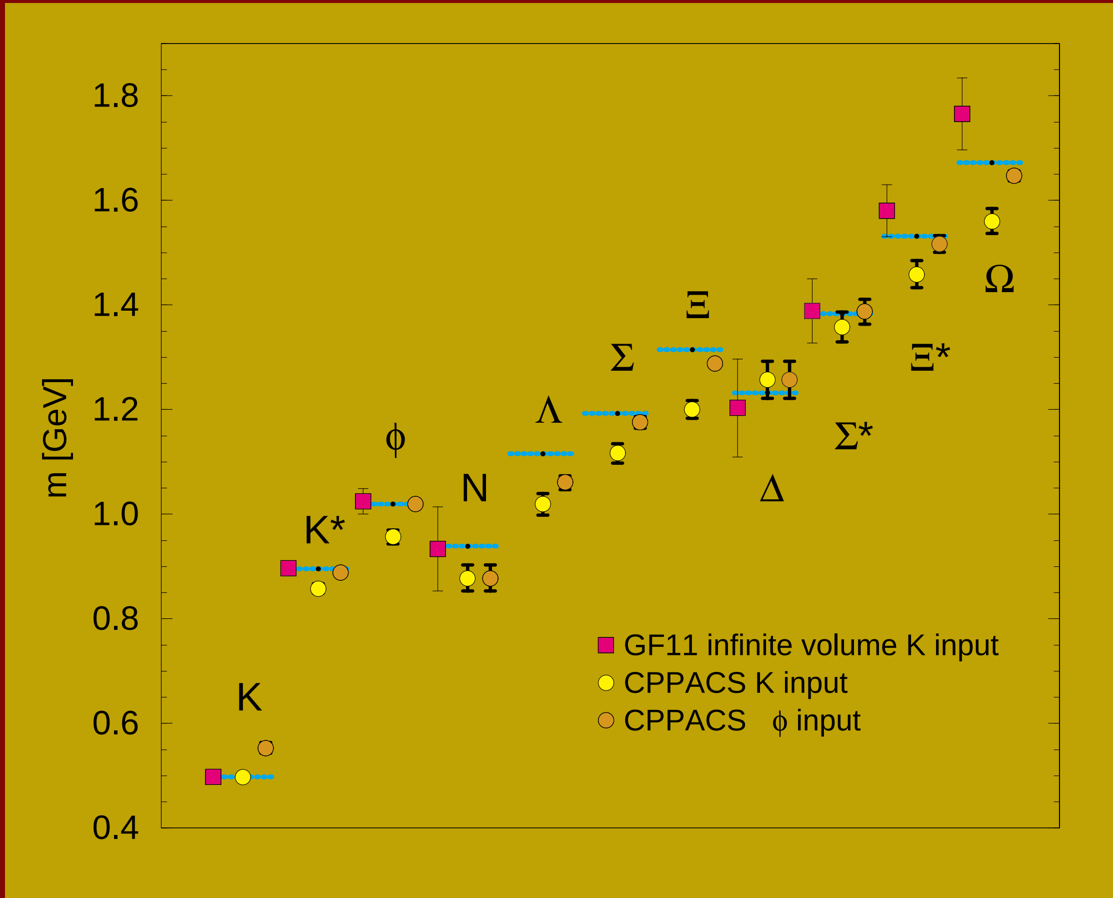
▷ Fermion masses and mixings; CP violation; neutrino oscillations

▷ What makes an electron an electron and a top quark a top quark?

Topography

▷ What is the fabric of space and time?

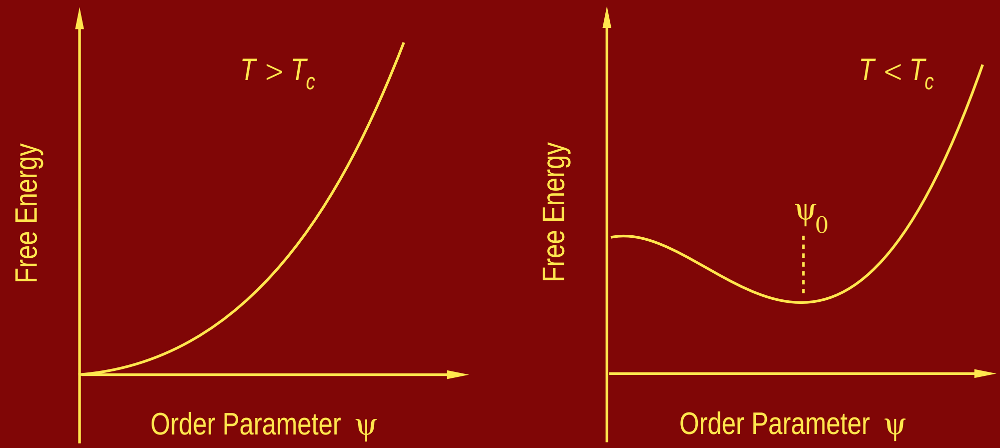
QCD explains the light hadron masses



For p, ρ, $[\pi]$, . . . , *confinement energy* is the source.

“Mass without mass”

Analogy to superconductivity sets M_W, M_Z



Meissner effect: EM fields disturb condensate of Cooper pairs

Weak bosons disturb Higgs condensate, acquire masses:

$$M_W^2 = \frac{g^2 v^2}{2} = \frac{\pi\alpha}{G_F\sqrt{2}\sin^2\theta_W}$$

$$M_Z^2 = \frac{M_W^2}{\cos^2\theta_W}$$

EW scale is $v = \left(G_{\mathrm{F}}\sqrt{2}\right)^{-\frac{1}{2}} \approx 246\ \mathrm{GeV}$

Disturbing EW condensate may generate fermion mass

$\boxed{\text{EWSB is necessary, not sufficient}}$

Standard model: each fermion mass $\Rightarrow$ new, *unknown* Yukawa coupling

$$\mathcal{L}^{(e)}_{\text{Yukawa}} = -\zeta_e \left[\overline{\mathsf{R}}(\phi^\dagger \mathsf{L}) + (\overline{\mathsf{L}}\phi)\mathsf{R} \right] .$$

$$\boxed{m_e = \zeta_e v/\sqrt{2}}$$

All fermion masses $\sim$ physics beyond the standard model!

$$\zeta_t \approx 1 \qquad \zeta_e \approx 3 \times 10^{-6} \qquad \zeta_\nu \approx 10^{-10} \;??$$

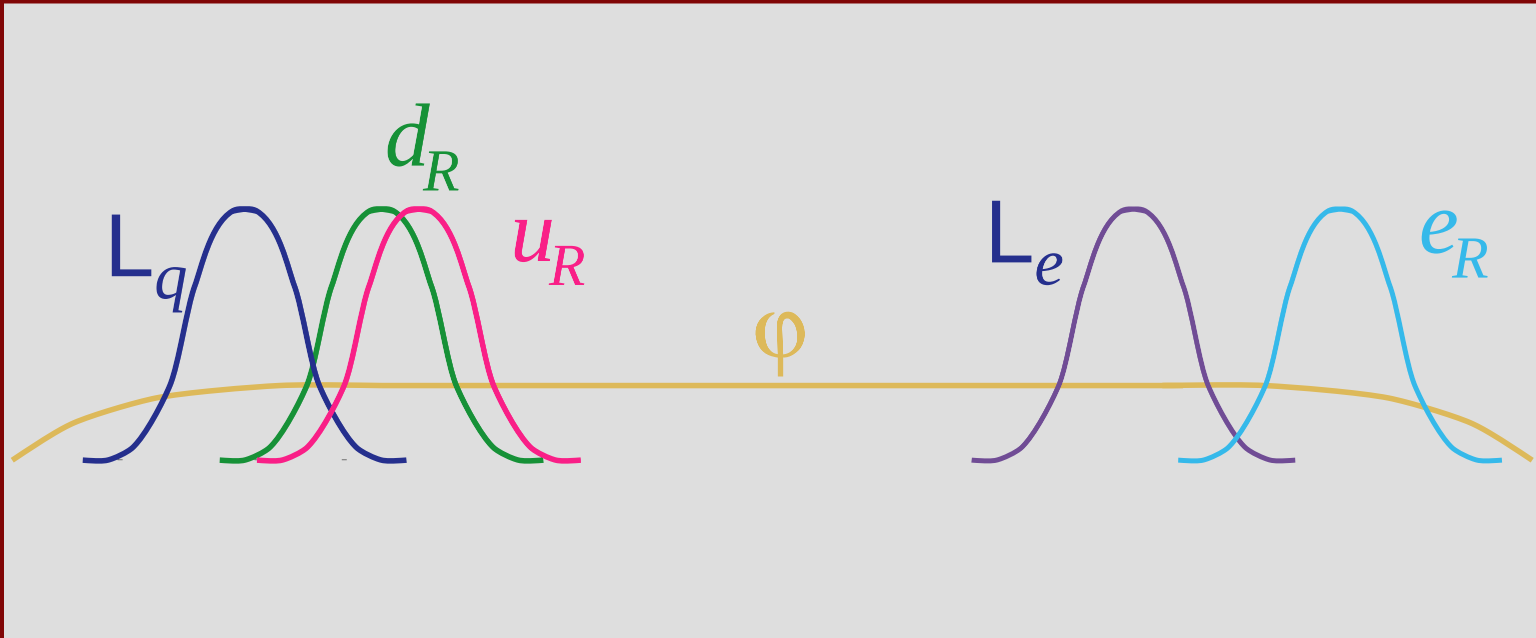
What accounts for the range and values of the Yukawa couplings?

There may be *other sources* of neutrino mass

Best hope until now:

Unified theories: pattern of fermion masses *simplifies* on high scales

Might Extra Dimensions Explain the Range of Fermion Masses?



Arkani-Hamed, Schmaltz, and Mirabelli:

Different fermions ride different tracks in the 5^{th} dimension

Small offsets in the new coordinate $\Rightarrow$ exponential differences in masses

Big Questions for Future Accelerators

- What machines are possible?
  When?
  At what cost?
  With what technical risk?

- What are the physics opportunities? the scientific risks?

- Can we do physics in the environment?
  (What does it take?)

- How will these experiments add to existing knowledge *when they are done?*

Circle Line Tours Seminar Series

http://www-theory.fnal.gov/CircleLine/

e^+e^- Linear Collider

A lovely idea!

Possible goals:

- multi-TeV to complement LHC studies of EWSB
- detailed studies of t or H or SUSY $\lesssim 500$ GeV?
- threshold scans of any new channel $\lesssim 1$ TeV?

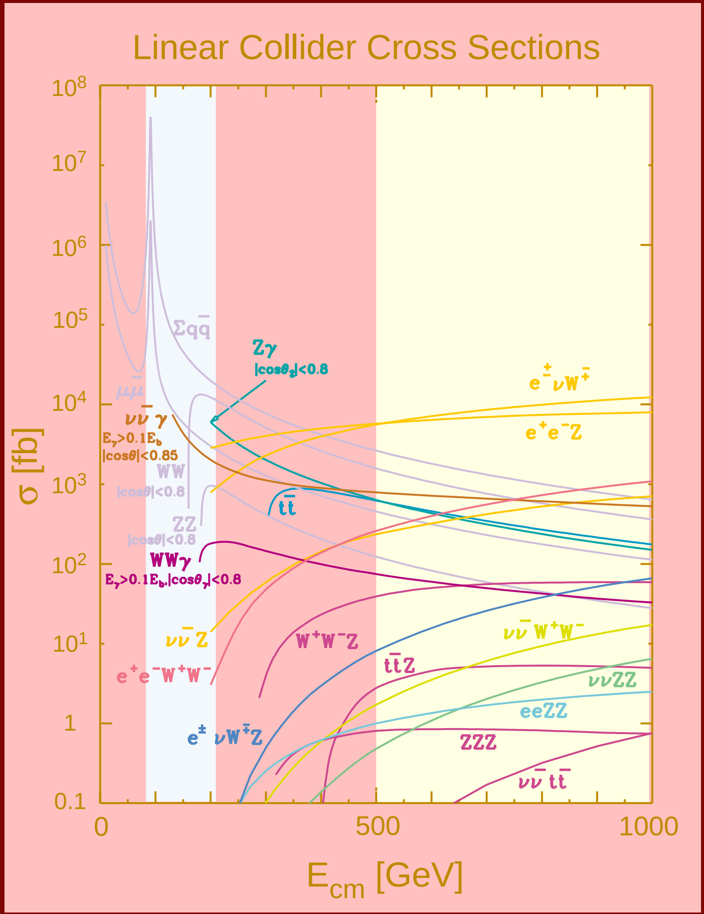
Traditional advantages:

- Point particle means full E_{cm} is available
- No background from the underlying event

Traditional challenges:

- Hard to reach very high energies
- Small cross sections demand high luminosity

Away from resonance peaks, cross sections are small . . .



. . . but many interesting cross sections are significant fractions of σ_{total}

H. Murayama and M. Peskin, "Physics Opportunities of e^+e^- Linear Colliders," *Ann. Rev. Nucl. Part. Sci.* **46,** 533 (1996).

E. Accomando, et al., "Physics with e^+e^- Linear Colliders," *Phys. Rep.* **299,** 1 (1998), hep-ph/9705442.

Some issues for a linear collider

- We would all love to have a multi-TeV linear collider today. We can't have one. How hard should we push two-beam (CLIC) technology?
- Does the physics promise of a 500-GeV linear collider justify the cost? (Has physics changed so much that this is the machine we should want?) (ALCS; P. Grannis at LCWS2000)
- How important is high luminosity to a 500-GeV LC? (ECFA/DESY) Which technology is most likely to provide it?
- If the case for a low-energy LC is so strong, how highly should we value a machine's potential for expansion? Should we build a low-energy, high-luminosity, non-expandable, inexpensive machine right away? (S. Komamiya)

. . . issues for a linear collider

- ▷ If supersymmetry justifies a low-energy linear collider, how expandable must the machine be to cover the SuSy waterfront? 800 GeV? 1 TeV? More?

- ▷ If supersymmetry makes the case for a 500-GeV LC, shouldn't we wait for supersymmetry to be discovered at the Tevatron or the LHC?

- ▷ If a light Higgs boson makes the case for a 500-GeV LC, shouldn't we wait for the Higgs boson to be discovered at the Tevatron or the LHC?

- ▷ How can we define the Right Linear Collider? (Kronfeld, *et al.* begin)

- ▷ Where is the community of users for a 500-GeV LC?

$\mu^+\mu^-$ collider

Possible path to a few-TeV $\ell^+\ell^-$ collider

to study electroweak symmetry breaking and explore . . .

μ: an elementary lepton $\Rightarrow$ energy efficient

synchrotron radiation not crippling

$\Rightarrow$ small device reaches 1-TeV scale

$\boxed{\text{?? modest size} \Rightarrow \text{modest cost ??}}$

But muons do decay—have to move fast!

Fierce detector (and machine) environment . . . the disc of death

$\boxed{\text{Ultimate goal is } \sqrt{s} \sim 4 \text{ TeV}}$ (keep eye on ball)

But ... How to start?

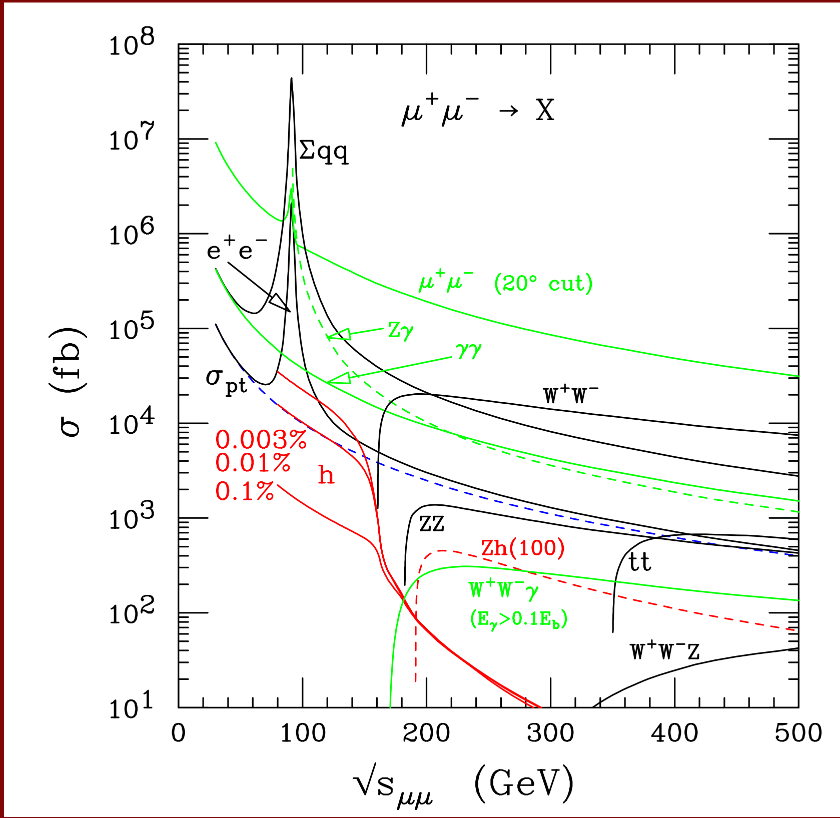
¶ A First Muon Collider?

- high-luminosity Z factory
- Higgs factory
- W^+W^-, $t\bar{t}$ threshold $\quad \sqrt{s} \approx \frac{1}{2}$ TeV to explore SUSY or Techni world

¶ Front-end physics

- intense low-energy hadron beams
- a copious source of low-energy muons
- Neutrino factory: intense ν_μ and $\bar{\nu}_e$ or $\bar{\nu}_\mu$ and ν_e beams

$\mu^+\mu^-$ Cross Sections



(h labels envelope of Higgs peak cross sections)

$\boxed{\text{Is } \mu^+\mu^- \to h \to b\bar{b} \text{ observable?}}$

The Ultimate Neutrino Source?

Muon storage ring with a millimole of muons per year.

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e \text{ OR } \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

μ charge, momentum, polarization determine
ν composition, spectrum.

Beam from μ^- contains ν_μ, $\bar{\nu}_e$, but no $\bar{\nu}_\mu$, ν_e, ν_τ, or $\bar{\nu}_\tau$.

- Oscillation studies over a wide range of distance/energy and at very great distances
- Deeply inelastic scattering on thin targets

Requires less muon cooling than a $\mu^+\mu^-$ collider.

νFact '99 · Lyon νFact 2000 · Monterey
Fermilab study, hep-ex/0008064

Some issues for a neutrino factory

- ▷ How rich is the program of neutrino oscillation measurements? Will the questions still be interesting when a neutrino factory operates?
- ▷ How many of the pressing questions could be answered using super-intense $\nu_\mu, \bar{\nu}_\mu$ beams generated by pion beams?
- ▷ Are mixed $\nu_\mu, \bar{\nu}_e$ beams a benefit or a curse?
  How important is muon polarization?
- ▷ Can we conceive a practical, large-volume detector that will identify e, μ, τ and measure their charges? If you could do it, what would it be worth to you?
- ▷ What is the right energy for a neutrino factory? Could some of the important physics be done at the Spallation Neutron Source?
- ▷ How can we define the Right Neutrino Factory?

Some issues for a $\mu^+\mu^-$ collider

- (Can any of this be done?)
- For a Higgs factory, what is the program of measurements a $\mu^+\mu^-$ collider could accomplish? Other than precise determinations of mass and width, what could you do to establish the nature of the Higgs boson?
- For a modest-energy $\mu^+\mu^-$ collider, can the luminosity be competitive with a linear collider? How great a disadvantage is the less-flexible polarization of the muon beams?
- For all energies, what compromises must be made for a detector to operate gracefully in the environment?
- Does small mean cheap? Does complicated mean expensive?

Beyond the LHC

Discoveries at LHC could point to energies well above the 1-TeV scale $\Rightarrow \sqrt{s} \gg 14$ TeV.

- Heavy Higgs boson
- New strong dynamics   strong WW scattering
  Gauge-mediated SUSY breaking   Technicolor
- New gauge bosons
- Hints of large extra dimensions

A Very Large Hadron Collider is the one multi-TeV machine we know we can build.

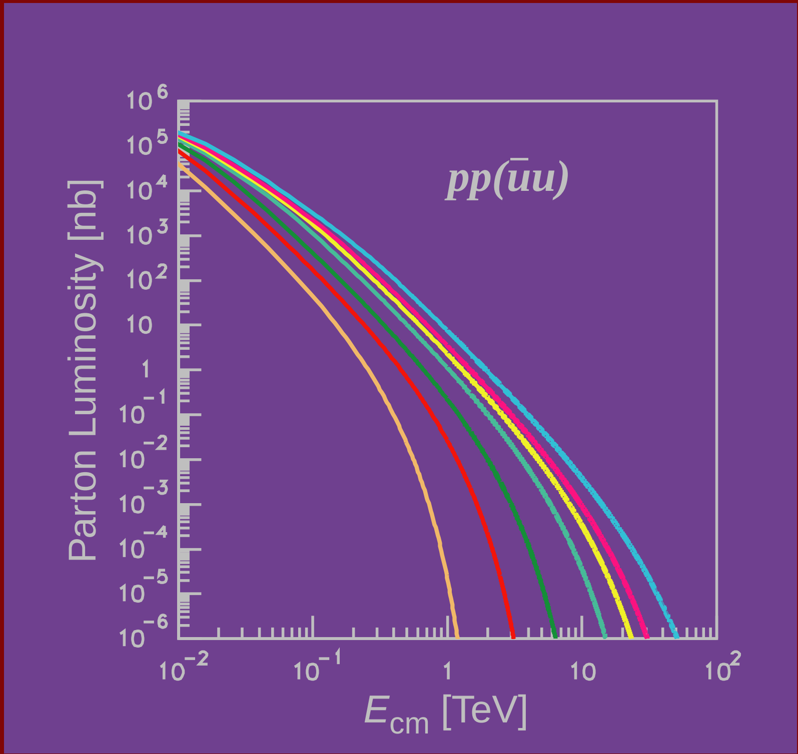
Pointlike cross sections $\propto 1/s \Rightarrow$ Luminosity goal:

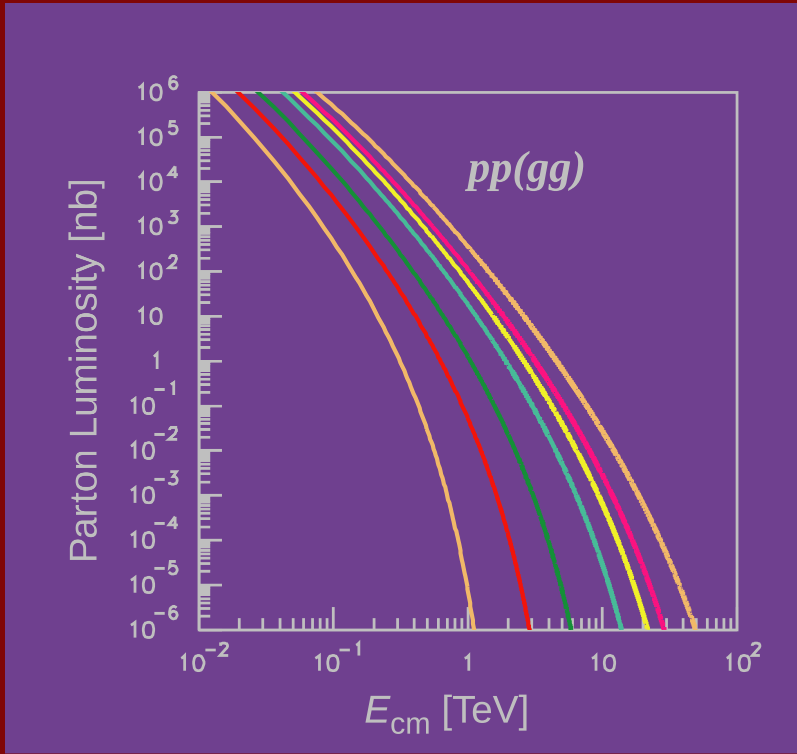
$$\mathcal{L}^{\star} = 10^{32\text{-}33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \left(\frac{\sqrt{s}}{40\ \mathrm{TeV}}\right)^2$$

For $\sqrt{s} = 100$ TeV, target $\mathcal{L}^{\star} \approx 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Parton Luminosities

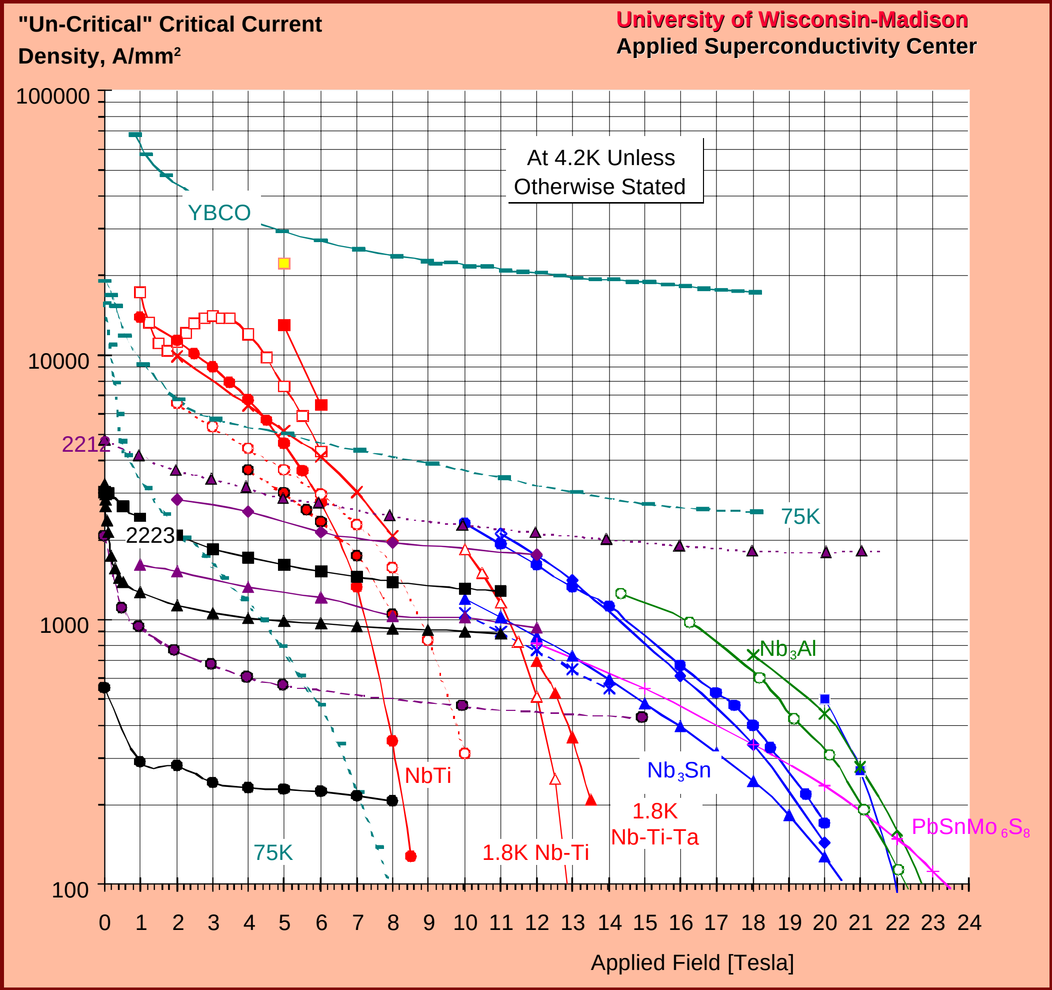
at $2, 6, 14, 40, 70, 100, 200$ TeV



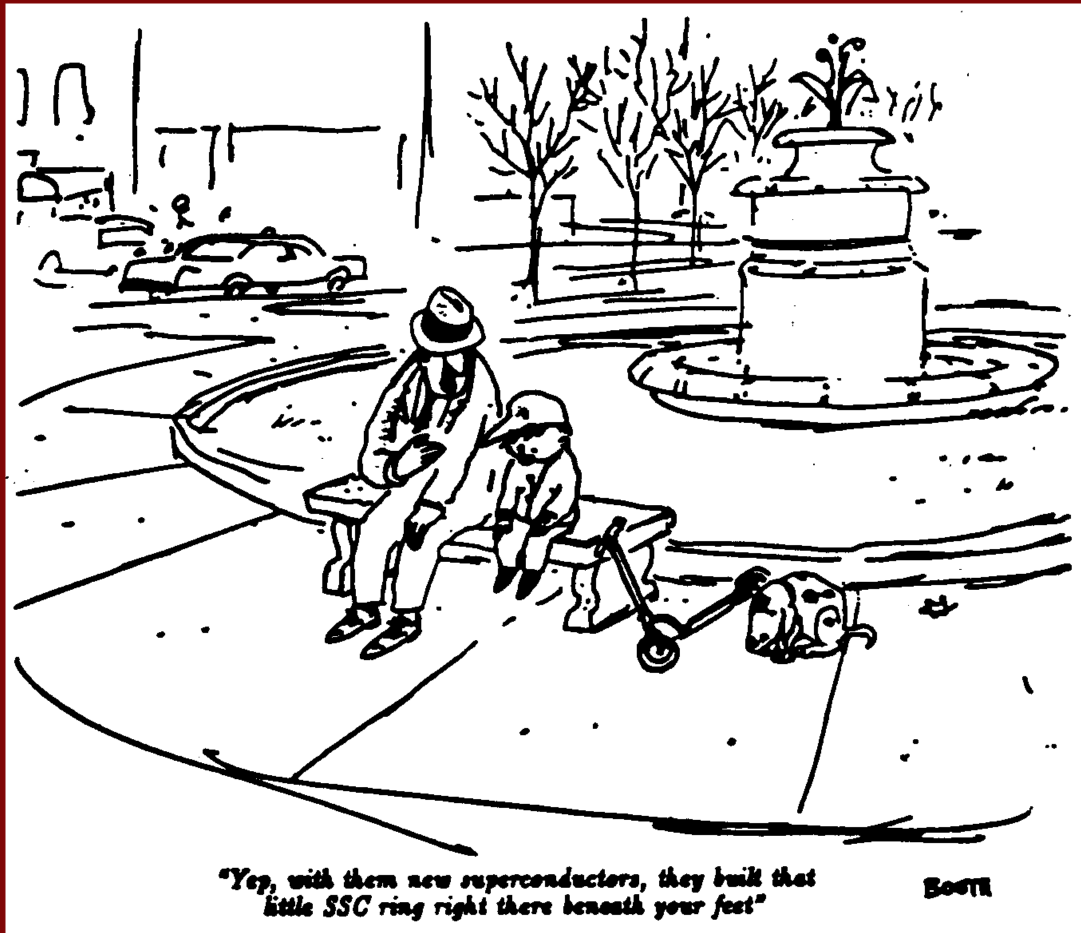


Background: E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, *Rev. Mod. Phys.* **56**, 579 (1984). (CTEQ5 parton distributions)

High-field magnets will require new superconductors



...but we can always dream



Poster illustration advertising a talk on high-T_c superconductors at the SSC Central Design Group.

Some issues for a VLHC

- ▷ (Cost reduction is essential to go beyond SSC.)
- ▷ Can we give a crisp scientific mission for a VLHC, or must we await returns from the LHC?
- ▷ Could a scientific community for the VLHC appear before LHC experiments have run their course?
- ▷ What are the energy / luminosity tradeoffs for detectors?
- ▷ What is the suite of experiments the VLHC could support? Are there compelling reasons to study special geometries?
- ▷ Are there intrinsic limitations to the performance of gargantuan accelerators? How could we learn to break through them?
- ▷ What role should heavy ions play in the design and exploitation of a VLHC?

The Road to Snowmass 2001

- A community event organized by the Division of Particles and Fields and Division of Physics of Beams of the American Physical Society
  Saturday, June 30 – Saturday, July 21, 2001 in Snowmass, Colorado
- Ron Davidson ⟨rdavidson@pppl.gov⟩ (DPB) and
  Chris Quigg ⟨quigg@fnal.gov⟩ (DPF) are leading the organization.
- The entire HEP community is welcome. We expect ≈ 500 participants.
- The agenda for Snowmass 2001 will be set by the community.
  We are working constructively with the laboratories and science agencies, and we will call on them for support. (Proposals in preparation)
- We are encouraging very significant international involvement, and are in regular communication with leaders from outside the U.S.


Snowmass Village
at Aspen

We have consulted broadly to formulate Snowmass 2001

- DPF and DPB executive committees
- Users organizations from Brookhaven, Cornell, Fermilab, and SLAC
- North-American physicists working at CERN and DESY
- Representatives of non-accelerator experiments
- Representatives of the linear collider, neutrino factory / muon collider, and very large hadron collider communities
- The accelerator research community
- Other physicists representing diverse backgrounds, interests, and experiences:
  nuclear physics community: neutrinos, QCD, . . .
- APS Presidential Line, Other APS officers and staff
- Directors of Cornell, Fermilab, and SLAC; CERN, DESY, and KEK
  Division Directors of Argonne, Brookhaven, Lawrence Berkeley National Lab, . . .
- Chair of HEPAP; DOE and NSF officials
- Numerous physicists from outside the United States

We have received much encouragement and many thoughtful suggestions.

Some Goals of Snowmass 2001

- Undertake a thematic survey of our vision of particle physics and its future in the most ambitious intellectual terms. Examine different scenarios for the new physics landscape. Within this broad vision, identify the questions we want to address over the next two decades.
- Looking far beyond the standard model to string theory and to clues that the coming precision cosmology might supply, understand what might lead us to identify new energy scales or frame new experimental programs.
- Consider the range of instruments that might help us achieve our scientific goals. Gain a community understanding of readiness, capabilities, costs, and technical risks of various accelerators proposed around the world. Articulate the accelerator R&D needed for near-term and longer-term projects.
- Explore fundamental research in accelerator physics and technology that will be needed to address our longer-term scientific goals.
- Educate and energize our community to create the future we want.
- Engage with the public, and with other scientists.

Snowmass 2001 will explore particle physics as a whole

- Experiments at the highest energies and experiments of exceptional sensitivity; experiments that explore very high scales through virtual effects
- Accelerators to address a broad range of scientific opportunitities; accelerator research—including its historical importance—to provide information for knowledgeable decisions about future projects, and accelerator research and technology development for the long term.
- Theory that develops hand-in-hand with experiment and visionary theory that hasn't yet engaged experimental particle physics directly

including ...

- Accelerator experiments and experiments that use natural sources (land, sea, and sky)
- Mature subjects and subjects just opening up
- The interplay between particle physics and technology
- The interaction of particle physics with related fields
- ...

Snowmass 2001 Organizing Committee

Particle Physics

Chris Quigg (DPF)
Sally Dawson (BNL)
Paul Grannis (Stony Brook)
David Gross (ITP/UCSB)
Joe Lykken (Fermilab)
Hitoshi Murayama (Berkeley)
René Ong (Chicago $\longrightarrow$ UCLA)
Natalie Roe (LBNL)
Heidi Schellman (Northwestern)
Maria Spiropulu (Chicago)

Accelerators & Technology

Ron Davidson (DPB)
Alex Chao (SLAC)
Alex Dragt (Maryland)
Gerry Dugan (Cornell)
Norbert Holtkamp (Fermilab)
Chan Joshi (UCLA)
Thomas Roser (BNL)
Ron Ruth (SLAC)
John Seeman (SLAC)
Jim Strait (Fermilab)

Related Particle Physics Events in Summer 2001

- 2001 Particle Accelerator Conference, 18 – 22 June 2001, Chicago, Illinois
- Physics in Collision, 28 – 30 June 2001, Seoul, South Korea
- 4th Edoardo Amaldi Conference on Gravitational Waves (Amaldi 2001) 7 – 12 July 2001, Perth, Australia
- International Conference on High Energy Physics of the European Physical Society 12 – 18 July 2001, Budapest, Hungary
- 16th International Conference on General Relativity and Gravitation (GR16) 15 – 21 July 2001, Durban, South Africa
- 2001 international Conference on Lepton–Photon Interactions 23 – 27 July 2001, Rome

Parallel event at the Aspen Center for Physics:

Electroweak Symmetry Breaking and TeV-Scale Physics After LEP

4-week workshop beginning July 7

Approximate Snowmass 2001 Working Groups

Electroweak Symmetry Breaking Flavor Physics Scales beyond 1 TeV Astro/Cosmo/Particle Physics QCD & strong interactions	Interaction Region Magnet technology RF technology Particle Sources Beam Dynamics Environmental Control High-Performance Computing Advanced Acceleration Techniques Diagnostics
μ storage rings and colliders High-sensitivity experiments e^+e^- colliders below M_Z e^+e^- linear (dominantly above M_Z) Hadron colliders (+ lepton-hadron) Astroparticle experiments Particle physics and technology	Muon-based systems e^+e^- circular colliders e^+e^- linear colliders Hadron colliders Lepton-hadron colliders High-intensity proton sources

The core of Snowmass—as usual—will be the work of individuals and working groups on scientific and technical issues . . .

. . . but the times and our situation demand additional special efforts:

▷ *Important involvement of students and young physicists*

- Subsidized housing for 50 students
- Young physicists throughout the organization

▷ Educating ourselves: *teach-ins* on

- Opportunities for accelerator research
- Experimental implications of string theory ?
- The role of nonaccelerator experiments in particle physics ?

▷ Educating ourselves: IEEE/NPSS *technology school*

- Short courses and lectures on advanced technologies sponsored by IEEE Nuclear & Plasma Sciences Society ($20K committed)

Committee for NPSS Technology Emphasis

Bruce C. Brown (Fermilab)

Matthew A. Allen (SLAC)

William M. Bugg (Tennessee)

Peter Clout (Vista Control Systems)

John E. Elias (Fermilab)

Erik Heijne (CERN)

Thomas Katsouleas (USC)

Ray S. Larsen (SLAC)

Patrick LeDu (Saclay)

Alan Todd (Advanced Energy Systems)

Craig L. Woody (Brookhaven)

Special efforts . . .

▷ Education and outreach

We plan an energetic and diverse program of outreach and education while in Snowmass, to reach the population of Aspen, Snowmass, and surrounding communities, and to display to all of us the many approaches to outreach our colleagues have put into practice.

- ◇ Public lectures and events; online event displays; Particle physics on the mall
- ◇ Physics vans
- ◇ Extensive-air-shower detectors at high schools
- ◇ (Particle) Physics activities in day camps
- ◇ Teacher training (Quarknet + local teachers)

“Science Weekend” in Snowmass, July 7/8, 2001

We will seek support from DOE & NSF, URA, APS, local sources, etc.

Snowmass 2001 Outreach Coordinating Committee

Elizabeth Simmons (Boston University)

Marge Bardeen (Fermilab)

Martin Berz (Michigan State)

Bill Frazer (Aspen Center for Physics)

Evalyn Gates (Chicago & Adler Planetarium)

Joey Huston (Michigan State)

Ronen Mir (SciTech)

Mel Month (Brookhaven)

Helen Quinn (SLAC)

Deborah Roudebush (Quarknet teacher, Virginia)

Greg Snow (Nebraska)

Ken Taylor (Quarknet teacher, Texas)

Jeff Wilkes (Washington)

. . .

We will produce three documents for the community

1) A brief and illustrated thematic survey of what particle physics is and aspires to be, guided by the scientific imperatives.

Comment: Documents proceeding from broad scientific goals to specific questions and then to instruments and technology development have been used to excellent effect by NASA. We will produce the thematic survey in final form at the summer study, *with professional help.* It should exist in several formats (printed page, web site, seminar materials, etc.), and in versions for different audiences, including the physics community and the wider public.

We will seek financial (and other) support for this activity

. . . three documents for the community

2) A survey of accelerator research and development

> ***a)*** highlighting the historical importance of accelerator R&D to our field, and to science and society at large;
>
> ***b)*** giving—in broad terms—the information that will be required for informed decisions about possible future accelerator projects;
>
> ***c)*** making the case for accelerator R&D not connected with specific projects

Comment: This document can accomplish several important goals. It will provide perspectives on future possibilities and on the importance of preparing for these futures, and it will make the case for all the important R&D activities.

Some Examples of Accelerator and Technology Topics

- Instruments or Proto-projects
  - VLHC / SuperLHC
  - Linear Colliders: NLC/TESLA/JLC, CLIC, giga-Z
  - Neutrino Factory
  - Muon Collider
  - High-luminosity B Factory; B Factory Upgrades
  - Bright proton source
  - τ-Charm Factory
  - Antiproton source / Antimatter Factory
  - Large circular e^+e^- colliders
  - Lepton-Hadron Colliders

- Technology Developments

magnet development	laser-based acceleration
high-frequency warm RF development	plasma-based acceleration
superconducting RF development	...
large-scale simulation	

- Fundamental limits in beams and acceleration technology

RF Breakdown limits	superconducting RF limits
limits to low emittance	materials limits.
quantum limits	...
magnetic field limits	

... three documents for the community

3) A more detailed, but still $<$ 100-page "white paper" on the field in all its richness and potential.

Comment: In the spirit of the 1994 DPF Committee on Long-Range Planning Report, this document can capture our community's sense of itself. Organized around scientific and technical goals, rather than laboratory programs, it can serve as important backdrop for future policy decisions.

Work carried out by individuals and working groups for the Summer Study will be reported in the *Proceedings.* We can include working documents or project status reports on a CD-ROM, and on the web. *We will explore innovative ways to publish the work of Snowmass 2001.* (Discussions with SLAC *e*Conf, *JHEP*)

Snowmass 2001 Needs You!

- Begin investing in *your future*.
- Come to Snowmass!
  We especially welcome younger physicists and advanced students.
- Give us ideas for the working groups, suggestions for convenors, thoughts on structure of the workshop.
- Help us create an atmosphere of inclusion and optimism
  —a sense of community
  The shoot-out mentality is our enemy (applies worldwide!)
- . . .